Chen, X., Wu, S., Wang, X., & Li, D. (2019). Optimal pricing strategy for the perishable food supply chain. *International Journal of Production Research*, *57*(9), 2755-2768. https://doi.org/10.1080/00207543.2018.1557352

Optimal pricing strategy for the perishable food supply chain

Xu Chen[a], Shuyao Wu[a], Xiaojun Wang[b], Dong Li[c]

a. School of Management and Economics, University of Electronic Science and Technology of China, Chengdu, 611731, China. E-mail: xchenxchen@263.net; wushuyao921@163.com.

b. Department of Management, University of Bristol, Bristol, BS8 1TZ, U.K. E-mail: xiaojun.wang@bristol.ac.uk

c. Management School, University of Liverpool, Liverpool, L69 3BX, U.K. E-mail: dongli@liv.ac.uk

Abstract: This research investigates the optimal pricing strategy for the perishable food supply chain. Using the setting of a two-echelon supply chain including a supplier and a retailer, we apply the game theory approach to derive the equilibriums for both a single pricing strategy and a two-stage pricing strategy. Through a comparison of the equilibriums, we explore how the two pricing strategies affect the supply chain's decisions and supplier's and retailer's performance individually and collectively. The results of the analysis show that the optimal choice of pricing strategy depends on the price markdown cost and its relationship with the two critical thresholds that are determined by a combination of factors including the potential market size, the price and quality sensitivity factors, the initial quality, the unit product cost, and the quality deterioration rate.

Keywords: perishable food; pricing strategy; supply chain coordination, supply chain management.

1. Introduction

Perishable foods, such as fresh produce, meat, seafood, bakery and cooked food, are basic necessities. A typical characteristic of perishable food is that its quality deteriorates continuously over time. At the same time, despite its critical role in the competition between grocery retailers, perishable food waste at grocery retailers due to damage, spoilage and other reasons is unacceptably high, estimated at approximately 15% (Wang and Li 2012). It is reported that in the world, 40-50% of all root crops, fruits, and vegetables are wasted (Gustavsson et al. 2011), representing not only a waste of production resources, but can also lead to hunger, poverty, income and economic growth decline (Wilem et al. 2014). In the United Kingdom (UK), supermarkets throw away at least 115,000 tons of food every year, the majority of which is perfectly good and eatable (the Telegraph 2016). According to the Food Rush (2016), 40% of the food produced in the United States (U.S.) goes uneaten, which leads to £160 billion of food waste annually, and supermarkets contribute 10% of the wasted food.

Operating in an extremely competitive market environment, revenue management for perishable foods becomes particularly important for supermarkets. Among various marketing and management tools, pricing strategy plays a crucial role and is a challenging task for grocery retail managers. Inappropriate pricing has an adverse effect on the management of perishable food, which may result in huge amounts of waste and reduce business revenue. Many supermarkets, e.g., Tesco in the UK and Ito Yokado in Japan, mark down the retail prices of fresh produce when they are approaching their expiration dates. However, the price discount policy is not applied to all the perishable foods in these supermarkets. In contrast, a single pricing strategy is applied to fresh produce in other supermarkets such as Wal-Mart stores in Chengdu, China. Furthermore, there is also media criticism that grocery retailers have driven food waste to the upstream of the food supply chain. According to a new report published by Feedback (2018), UK supermarkets drive food overproduction and waste on farms estimated at 2.5 million tons of food waste with an associated cost of £0.8 billion. Therefore, there are two natural questions that arise:

(1) Which pricing strategy should be adopted by the grocery retailer?

(2) How do different pricing strategies affect the performance of the retailer, the supplier

and the whole food supply chain?

To investigate the above questions, we consider a two-echelon supply chain including an upstream supplier and a downstream retailer. The retailer orders perishable food from the supplier and then sells to the end users during the demand period. Game theoretical approach is used to model two pricing strategies: a single pricing strategy and a two-stage pricing strategy for the perishable food supply chain. We seek to understand the effect of pricing strategy on the perishable food supply chain's decisions and performance by analyzing the equilibriums of the single pricing strategy and the two-stage pricing strategy.

This research makes several contributions. First, this research complements existing studies (Wang and Li 2012; Herbon et al. 2014; Wang et al. 2016) on perishable food pricing strategies by extending the investigation on the optimal pricing strategy from the retail end to the whole food supply chain. Our research does not only examine the impact of two pricing strategies on the retailer's pricing decisions and profits but also the supplier's wholesale price decision and the performance of the whole food supply chain individually and collectively. Second, different from studies on dynamic pricing strategies (Liu et al. 2015; Adenso-Díaz et al. 2017; Li and Wang 2017), our analysis focuses on two pricing strategies that are commonly adopted by grocery retailers worldwide. Furthermore, we do not only derive the optimal retail prices but also the timing of price markdown for the two-stage pricing strategy. Finally, our research also provides some important managerial implications that are useful for food retailers and suppliers to make strategic and operational decisions to manage perishable foods effectively.

The remainder of this paper is organized as follows: Section 2 provides a review of relevant research. Next, both the single pricing model and the two-stage pricing model are presented in Section 3. Section 4 examines the impact of pricing strategies on supply chain decisions and profits, and then explores the optimal choice of pricing strategy. Numerical analysis is presented to examine the effect of key parameters on decisions and performance in Section 5. Finally, we present concluding remarks highlighting key findings, managerial implications, and suggestions for future research in Section 6.

2. Literature review

Numerous prior studies have been conducted on the perishable food supply chain from approaches such as quality (Aung and Chang 2014; He et al. 2018), planning models (Ahumada and Villalobos 2009; Soto-Silva et al. 2016) and sustainability (Beske et al. 2014; Li et al. 2014). In this section, we will review the more relevant literature to this study by focusing on two key streams: (1) the shelf life management of perishable foods and (2) the pricing strategy for perishable foods.

Due to continuous public scrutiny of agricultural food supply chain practices, there have been an increasing number of studies on perishable food supply chain management in recent years. Despite growing public and academic attention, Ahumada and Villalobos (2009) pointed out in their comprehensive review of application of the agriculture-food supply chain planning models that although shelf life features are critical in assuring the freshness and quality of perishable foods, there is a lack of research that incorporates shelf life features into perishable food supply chain planning models. The rapid technological development in the last two decades, particularly in information technologies such as global positioning systems, radio frequency identification (RFID) systems, and time-temperature indicators (TTI), has made a significant impact on perishable food supply chain management (Li et al. 2014; Soto-Silva et al. 2016). Blackburn and Scudder (2009) introduced the concept of the marginal cost of time, the rate at which the product loses value over time in the supply chain, in their model to analyze the supply chain strategy for perishable products. Rong et al. (2011) incorporated product quality in food supply chain modeling and integrated the important aspects of controlling temperature and managing product quality in the decision making in the fresh food supply chain management. In the context of a fresh produce supply chain, Yu and Nagurney (2013) considered food deterioration and discarding costs of spoiled products in a network-based competitive food supply chain model and evaluated alternative technologies associated with different supply chain activities. Aung and Chang (2014) found that in a cold chain, compared to the traditional visual assessment method, sensor-based real-time quality monitoring and assessment methods are superior in managing product quality. La Scalia et al. (2016) applied radio frequency sensors allocated inside the smart logistic unit to food supply chain management in order to ensure the product shelf life and achieve logistics efficiency and system sustainability. Considering disruption risk and product deterioration, Huang et al. (2018a) investigated the optimal solutions for prices, preservation of investment and inventory in a three-level food supply chain setting. Zhu et al. (2018) provided a model-oriented review to understand the context-specific applications of operational research techniques in the sustainable food supply chain domain. However, the majority of this research stream concentrates on supply chain planning or inventory control for perishable food supply chains and less attention has been given to pricing strategy as an important tool to manage perishable foods.

Firms' technological investments in perishable products management in the food or other industry sectors is often combined with other operational decisions such as pricing or inventory control (Blackburn and Scudder 2009; Dolgui et al. 2008; He et al. 2018; Huang et al. 2018b; Navarro et al. 2018). Many inventory or supply chain models have been proposed in either deterministic (Wang et al. 2010; Cai et al. 2013; Qin et al. 2014; Li and Wang 2017) or stochastic (Modak et al. 2016; Tiwari et al. 2017; Roya et al. 2006; 2018) demand settings with the aim of total cost minimization or profit maximization through an optimal set of pricing, ordering quantity, and investment level. Another relevant research stream focuses on the pricing practices of perishable food products since pricing strategy has a significant impact on a firm's revenue. Among them, dynamic pricing strategies have been explored extensively. Herbon et al. (2014) developed a dynamic pricing model for perishable product inventory management with the support of a TTI-based automatic detection device. Considering a price- and quality-sensitive demand, Liu et al. (2015) incorporated quality degradation into a perishable food inventory model to simultaneously determine the dynamic pricing strategy and investment strategy. Li and Wang (2017) presented an application of a sensor data-enabled supply chain dynamic pricing model for perishable food. Although their research shows the potential benefits of big data-driven chilled food supply chain innovation, the implementation of dynamic pricing strategies is not straightforward for most grocery retailers (Wang and Li 2012; Lu et al. 2018). Adenso-Díaz et al. (2017) proposed a deterministic mathematical model to evaluate the impact of dynamic pricing strategies on revenues and spoilage. Their analysis found that on the one hand, a dynamic price strategy leads to food spoilage reduction, and on the other hand, it can have a negative or positive impact on a firm's total revenue depending on the speed of the price discounting strategy and the specific scenario. However, the cost of price adjustment was not considered in their study. This price adjustment cost accounts for a substantial portion of operational cost and can significantly influence firms' decisions about dynamic pricing. Considering the price adjustment cost, Lu et al. (2018) proposed a suboptimal pricing strategy that includes both static pricing and dynamic pricing throughout the entire planning period. Nevertheless, the dynamic pricing model does not consider how consumer will react under this price strategy and some consumers may delay the time of their purchase, anticipating a lower price.

More relevant to the setting of this work, Wang and Li (2012) proposed a pricing approach based on dynamically identified food shelf life supported by tracking and tracing technologies. Although different pricing policies are explored following grocery retailers' current practices, the analysis mainly focuses on how much a retailer should charge and discount but not the discount timing. Qin et al. (2014) proposed a joint pricing and inventory control model for perishable foods with an assumption that the quality and physical quantity of fresh produce deteriorate simultaneously over time. In their simulation study of the impact of price discounting frequency on a retailer's performance, Chung and Li (2014) found that two-period and multiperiod pricing strategies deliver better performance than single-period pricing. Under the consumer price fairness perception, Wang et al. (2016) developed an optimal price markdown policy for perishable food considering the trade-offs between the food retailer's revenue and the consumer's utility. Nevertheless, most of the previously mentioned studies only consider pricing strategies from the retailer's perspective. It is not clear how the pricing strategies adopted by the retailer affect suppliers' decisions and the performance of the perishable food supply chain as a whole. This study fulfils this research gap by looking at two commonly adopted pricing practices and examining their impacts on operational decisions and the collective and individual performance for both the retailer and supplier with a consideration of continuous quality deterioration.

3. The model and equilibrium analysis

3.1 The model

We consider a two-echelon supply chain composed of a supplier and a retailer, who orders perishable food from the supplier and then sells it to consumers. We assume the supply chain power structure is vertical Nash, that is, there is a balanced power relationship between the retailer and the supplier. This type of supply chain power relationship is common both in the supply chain management literature (Choi 1996; Chen et al. 2016; Luo et al. 2017) and in practice (Wilhelm 2016). The notation used in this paper is displayed in Table 1.

Table 1. Notation

c	Unit product cost
w_1	Unit wholesale price with retailer's single pricing strategy
w_2	Unit wholesale price with retailer's two-stage pricing strategy
$f(t)$	Demand rate
$p(t)$	Unit retail price
p_1	Unit retail price with single pricing strategy
p_{21}	First-stage unit retail price with two-stage pricing strategy
p_{22}	Second-stage unit retail price with two-stage pricing strategy
m_1	Retailer's marginal profit with single pricing strategy, $p_1 = w_1 + m_1$
m_{21}	Retailer's first-stage marginal profit with two-stage pricing strategy, $p_{21} = w_2 + m_{21}$
m_{22}	Retailer's second-stage marginal profit with two-stage pricing strategy, $p_{22} = w_2 + m_{22}$
T	Sale period
T_1	Retailer's markdown time with two-stage pricing strategy
M	Retailer's markdown cost
M_1	Retailer's price markdown cost critical threshold
M_2	Supply chain's price markdown cost critical threshold
$\pi_{r1}(p_1)$	Retailer's profit with single pricing strategy
$\pi_{s1}(w_1)$	Supplier's profit with single pricing strategy
$\pi_{r2}(p_{21}, p_{22}, T_1)$	Retailer's profit with two-stage pricing strategy
$\pi_{s2}(w_2)$	Supplier's profit with two-stage pricing strategy
Π_1	Supply chain's total profit with single pricing strategy
Π_2	Supply chain's total profit with two-stage pricing strategy

In alignment with prior studies (e.g., Tsiros and Heilman 2013; Wang and Li 2012), we use the following demand function:

$$f(t) = D_0 - \alpha p(t) + \beta q(t)$$

The customer demand is influenced by retail price and product quality. D_0 is the potential market size, α is the price sensitivity factor, and β represents the quality sensitivity factor. Among the existing perishable food management literature, food quality is often modeled as a decreasing parameter which depends on the time under the required preservation conditions (Blackburn and Scudder 2009; Wang and Li 2012; He et al. 2018). Here, $q(t) = q_0 - \lambda t$ indicates the quality level, which is determined by the initial quality (q_0) and the deterioration rate (λ). The sale period (T) is determined by the demand rate, and the sale is finished when $f(t) = 0$. Instead of making quality a decision variable, we set retail and wholesale prices and timing of the pricing discount as the decision variables.

3.2 Single-pricing model

In the single-pricing model, $p(t) = p_1$, that is, the unit retail price is constant during the demand period $(0, T)$. The demand faced by the retailer in the single pricing model, denoted by D_1, is $D_1 = \int_0^T [D_0 - \alpha p_1 + \beta(q_0 - \lambda t)]dt = (D_0 - \alpha p_1 + \beta q_0)T - \frac{1}{2}\beta\lambda T^2$. The decision problem faced by the retailer is to set the optimal retail price (p_1) to maximize his profit ($\pi_{r1}(p_1)$), and the decision problem faced by the supplier is to set the optimal wholesale price (w_1) to maximize his profit ($\pi_{s1}(w_1)$).

The retailer's profit with the single pricing strategy ($\pi_{r1}(p_1)$) is

$$\pi_{r1}(p_1) = (p_1 - w_1)[(D_0 - \alpha p_1 + \beta q_0)T - \frac{1}{2}\beta\lambda T^2] \tag{1}$$

The first part of the formula is the unit profit margin for the retailer, and the second part is the demand faced by the retailer.

Similarly, the supplier's profit with the single pricing strategy ($\pi_{s1}(w_1)$) is

$$\pi_{s1}(w_1) = (w_1 - c)[(D_0 - \alpha p_1 + \beta q_0)T - \frac{1}{2}\beta\lambda T^2] \tag{2}$$

The first part of the formula is the unit profit margin for the supplier, and the second part is the demand faced by the supplier

The supply chain's profit with the single pricing strategy (Π_1) is

$$\Pi_1 = \pi_{r1}(p_1) + \pi_{s1}(w_1) \tag{3}$$

As to the retailer's optimal retail price (p_1^*) and the supplier's optimal wholesale price (w_1^*)

with the single pricing strategy, we obtain the following lemma.

Lemma 1: $\boldsymbol{p_1^* = \frac{c\alpha + D_0 + \beta q_0}{2\alpha}}$ ***and*** $\boldsymbol{w_1^* = \frac{3c\alpha + D_0 + \beta q_0}{4\alpha}}$**.**

This lemma means that the retailer's optimal retail price (p_1^*) and the supplier's optimal wholesale price (w_1^*) with the single pricing strategy exist and are unique.

3.3 Two-stage pricing model

In the two-stage pricing model, the retail price is a piecewise function as follows:

$$p_2(t) = \begin{cases} p_{21} & 0 < t < T_1 \\ p_{22} & T_1 < t < T \end{cases}$$

The demand faced by the retailer in the two-stage pricing model, denoted by D_2, is $D_2 = \int_0^{T_1} (D_0 - \alpha p_{21} + \beta(q_0 - \lambda t))\,\mathrm{d}t + \int_{T_1}^{T} (D_0 - \alpha p_{22} + \beta(q_0 - \lambda t))\,\mathrm{d}t$. The retailer's decision problem is to set the optimal retail prices (p_{21}, p_{22}) and markdown time (T_1) to maximize his profit ($\pi_{r2}(p_{21}, p_{22}, T_1)$), and the supplier's decision problem is to set the optimal wholesale price (w_2) to maximize his profit ($\pi_{s2}(w_2)$).

The retailer's profit with the two-stage pricing strategy ($\pi_{r2}(p_{21}, p_{22}, T_1)$) is

$$\pi_{r2}(p_{21}, p_{22}, T_1) = p_{21} \int_0^{T_1} \big(D_0 - \alpha p_{21} + \beta(q_0 - \lambda t)\big)\,dt$$

$$+ p_{22} \int_{T_1}^{T} \big(D_0 - \alpha p_{22} + \beta(q_0 - \lambda t)\big)\,dt - w_2\, D_2 - M \quad (4)$$

The first part of the formula is the revenue from the first stage sales, and the second part is the revenue from the second stage sales. The last two parts represent the wholesale cost and markdown cost, respectively.

Similarly, the supplier's profit with the two-stage pricing strategy ($\pi_{s2}(w_2)$) is

$$\pi_{s2}(w_2) = (w_2 - c)\Big[\int_0^{T_1} \big(D_0 - \alpha p_{21} + \beta(q_0 - \lambda t)\big)\,\mathrm{d}t$$

$$+ \int_{T_1}^{T} (D_0 - \alpha p_{22} + \beta(q_0 - \lambda t))\,\mathrm{d}t\Big] \quad (5)$$

The first part of the formula represents the supplier's marginal profit, and the second part represents the market demand during the sale period.

The supply chain's profit with the two-stage pricing strategy (Π_2) is

$$\Pi_1 = \pi_{r2}(p_{21}, p_{22}, T_1) + \pi_{s2}(w_2) \quad (6)$$

As to the retailer's optimal retail prices (p_{21}^*, p_{22}^*), markdown time (T_1^*) and the supplier's optimal wholesale price (w_2^*) with the two-stage pricing strategy, we obtain the following lemma.

Lemma 2: $\boldsymbol{p_{21}^* = \frac{6c\alpha+7D_0+7\beta q_0}{13\alpha}}$, $\boldsymbol{p_{22}^* = \frac{8c\alpha+5D_0+5\beta q_0}{13\alpha}}$, $\boldsymbol{T_1^* = \frac{4(D_0+\beta q_0-c\alpha)}{13\beta\lambda}}$ ***and*** $\boldsymbol{w_2^* = \frac{10c\alpha+3D_0+3\beta q_0}{13\alpha}}$**.**

This lemma means that the retailer's optimal retail prices (p_{21}^*, p_{22}^*), markdown time (T_1^*) and the supplier's optimal wholesale price (w_2^*) with the two-stage pricing strategy exist and are unique. From lemma 2, we can also see that the quality deterioration rate (λ) does not have any impact on the optimal decisions of the initial retailer price, the markdown price and the wholesale price. However, the deterioration rate directly affects the optimal price markdown time (T_1^*). A large rate, which means the quality of perishable food deteriorates rapidly, will cause the markdown time to come earlier during the sales period.

4. Evaluate optimal pricing strategies for the perishable food supply chain

In this section, we discuss the effects of retailers' pricing strategies on the supply chain's decisions and profits, and then evaluate the optimal pricing strategy.

4.1 The effect of pricing strategy on decisions

Regarding the effect of retailers' pricing strategy on the supply chain's pricing decisions, we derive the following proposition.

Proposition 1: $\boldsymbol{p_{21}^* > p_1^* > p_{22}^*}$ ***and*** $\boldsymbol{w_1^* > w_2^*}$**.**

This proposition indicates that with the two-stage pricing strategy, the retailer sets a higher retail price in the first stage than the optimal retail price with the single pricing strategy and then marks down the price in the second stage. Interestingly, the supplier sets a higher wholesale price with the single pricing strategy than that with the two-stage pricing strategy. Intuitively, the retailer will order more products with the two-stage pricing strategy than with the single pricing strategy, and the supplier then sets a lower wholesale price with the two-stage pricing strategy.

4.2 The effect of pricing strategy on profits

Regarding the effect of retailers' pricing strategy on the optimal retailer profits, the supplier and the supply chain, we obtain the following proposition.

Proposition 2:

(1) If $\mathbf{0 < M < M_1}$ *, then* $\boldsymbol{\pi_{r2}(p_{21}^*,\ p_{22}^*,\ T_1^*) > \pi_{r1}(p_1^*)}$*; if* $\mathbf{M > M_1}$ *, then* $\boldsymbol{\pi_{r2}(p_{21}^*,\ p_{22}^*,\ T_1^*) < \pi_{r1}(p_1^*)}$.

(2) $\boldsymbol{\pi_{s2}(w_2^*) > \pi_{s1}(w_1^*)}$.

(3) If $\mathbf{0 < M < M_2}$*, then* $\boldsymbol{\Pi_2^* > \Pi_1^*}$*; if* $\mathbf{M > M_2}$*, then* $\boldsymbol{\Pi_2^* < \Pi_1^*}$.

$\boldsymbol{M_1 = \frac{363(D_0+\beta q_0-c\alpha)^3}{70304\alpha\beta\lambda}}$, $\boldsymbol{M_2 = \frac{235(D_0+\beta q_0-c\alpha)^3}{35152\alpha\beta\lambda}}$. $\boldsymbol{M_2 > M_1}$.

From this proposition, we find that, for the retailer, whether the two-stage pricing strategy delivers superior financial performance compared to the single pricing strategy is determined by the price markdown cost (M) and its relationship with a price markdown cost critical threshold (M_1). If the markdown cost is lower than the threshold ($0 < M < M_1$), then the retailer gains more profits with the two-stage pricing strategy than for the single pricing strategy. Otherwise, the single pricing strategy produces superior performance for the retailer. Intuitively, a high cost of price adjustment will have a negative impact on retailers' revenues. This is the main reason that many retailers avoid more regular price adjustment despite the continuous quality degradation of perishable foods, which is in line with the findings of previous studies in the literature (Wang and Li 2012; Lu et al. 2018). Surprisingly, the critical threshold (M_1) is a decreasing function of λ. This means that fast quality degradation will decrease the value of the critical threshold (M_1). Nevertheless, apart from quality deterioration rate, this critical threshold is also influenced by many other factors including the potential market size (D_0), the price and quality sensitivities (α and β), the initial quality (q_0), and the unit product cost (c). In this case, the combination of these factors has a stronger influence on the retailer's optimal pricing strategy than the quality deterioration rate.

For the supplier, this proposition means that the supplier's maximum profit with the two-stage pricing strategy is always higher than with the single pricing strategy. This is due to the fact that the two-stage pricing strategy generates higher customer demand than the single pricing strategy because the second stage price set in the price markdown time period enables capture of the value loss of perishable foods in the demand period. Despite a lower wholesale price as shown in Proposition 1, the supplier can gain more profit because of higher demand. As a result, the supplier has the incentive to motivate the retailer to adopt the two-stage pricing strategy.

For the whole food supply chain, this proposition means that whether the whole supply chain will benefit from the two-stage pricing strategy depends on the price markdown cost (M) and its relationship with a price markdown cost critical threshold (M_2). If the markdown cost is lower than the critical threshold ($0 < M < M_2$), then the supply chain's maximum profit with the two-stage pricing strategy is higher than with the single pricing strategy. Otherwise, the single pricing strategy generates more profit for the perishable food supply chain. Similar to M_1, M_2 is a decreasing function of λ and is also influenced by many other factors including the potential market size (D_0), the price and quality sensitivities (α and β), the initial quality (q_0), and the unit product cost (c). Nevertheless, the value of M_2 is higher than M_1 ($M_2 > M_1$), which means that, to gain benefit from the two-stage pricing strategy, the requirement of price markdown cost is less strict for the whole perishable supply chain than for the retailer.

4.3 The choice of pricing strategy

Based on the analysis of the effects of different pricing strategies on the profits of the retailer, the supplier and the whole supply chain, we can derive the following corollary on the choice of pricing strategy (shown in Figure 1).

Corollary 1:

(1) ***If*** $0 < M < M_1$, ***then*** $\pi_{r2}(p_{21}^*, p_{22}^*, T_1^*) > \pi_{r1}(p_1^*)$ ***and*** $\pi_{s2}(w_2^*) > \pi_{s1}(w_1^*)$;

(2) ***If*** $M_1 < M < M_2$, ***then*** $\pi_{r2}(p_{21}^*, p_{22}^*, T_1^*) < \pi_{r1}(p_1^*)$, $\pi_{s2}(w_2^*) > \pi_{s1}(w_1^*)$ ***and*** $\Pi_2^* > \Pi_1^*$;

(3) If $M > M_2$, ***then*** $\pi_{r2}(p_{21}^*, p_{22}^*, T_1^*) < \pi_{r1}(p_1^*)$, $\pi_{s2}(w_2^*) > \pi_{s1}(w_1^*)$ ***and*** $\Pi_2^* < \Pi_1^*$.

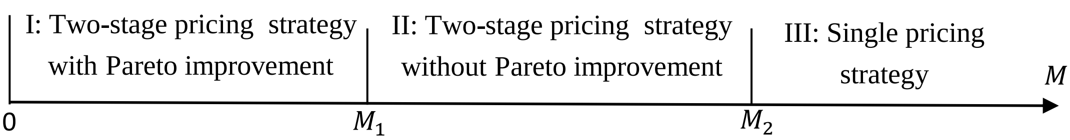


Figure 1 Choice of pricing strategy

Corollary 1 means that the selection of optimal pricing strategy is decided by the markdown cost (M) and its relationship with two critical thresholds (M_1 and M_2). Figure 1 illustrates the three decision regions for the optimal pricing strategy: a two-stage pricing strategy with Pareto improvement (Region I), a two-stage pricing strategy without Pareto improvement (Region II), and a single pricing strategy (Region III).

Region I: If the markdown cost is lower than the critical threshold, M_1, $(0 < M < M_1)$, then both the supplier and retailer gain more profits with the two-stage pricing strategy than with the single pricing strategy. Therefore, the two-stage pricing strategy benefits both the supplier and retailer. We call this scenario the *two-stage pricing strategy with Pareto improvement*. Under this condition, both the retailer and supplier should embrace the two-stage pricing stage to maximize their benefits.

Region II: If the value of the markdown cost is in the interval between the two thresholds $(M_1 < M < M_2)$, then the whole supply chain gains more profit with the two-stage pricing strategy than with the single pricing strategy, but the retailer gains less profit with the two-stage pricing strategy than with the single pricing strategy. We call this scenario the *two-stage pricing strategy without Pareto improvement*. From the retailer's perspective, in order to benefit from such a scenario, they should explore possible ways to reduce the price adjustment cost or persuade the supplier to share some of the increased profit. From the supplier's perspective, they should encourage the retailer to accept the two-stage pricing strategy through coordination mechanisms such as a profit-sharing contract to achieve a win-win situation for both supply chain parties. The optimal design for a profit-sharing contract will be explored in the next section.

Region III: If the markdown cost is higher than the critical threshold, M_2 $(M > M_2)$, then the retailer gains less profit with the two-stage pricing strategy than with the single pricing strategy and the same result applies to the whole perishable food supply chain. In this scenario, the price adjustment cost is too high for the perishable food supply chain to implement the two-stage pricing strategy, and therefore the single pricing strategy is the optimal pricing strategy.

4.4 Profit sharing contract design

As shown in Figure 1, in the scenario of *two-stage pricing strategy without Pareto improvement*, the two-stage pricing strategy hurts the retailer but benefits both the supplier and the supply chain. Then, the supplier has an incentive and the potential to induce the retailer to adopt the two-stage pricing strategy. In this case, a profit-sharing contract between the supplier and the retailer is explored. We assume that ρ is the supplier's profit-sharing ratio to the retailer, which measures the proportion that the retailer shares the supplier's profit.

Based on the above assumption, the following proposition is obtained.

Proposition 3: $\boldsymbol{\rho \in (\underline{\rho}, \overline{\rho})}$. ***Where*** $\boldsymbol{\underline{\rho} = \frac{2197M\alpha\beta\lambda}{72(D_0+\beta q_0-c\alpha)^3} - \frac{121}{768}}$ ***and*** $\boldsymbol{\overline{\rho} = \frac{107}{2304}}$.

This proposition means that a profit-sharing contract can coordinate the perishable food supply chain by redistributing the profits between the supplier and the retailer. When the supplier's profit-sharing ratio (ρ) is within the lower bound ($\underline{\rho}$) and the upper bound ($\bar{\rho}$), both the supplier and the retailer can gain more profits with the two-stage pricing strategy than with the single pricing strategy and achieve *Pareto* improvement. In this situation, the optimal design of a profit-sharing contract is therefore important to achieve a win-win situation for the supply chain.

5. Numerical analysis and managerial implications

In this section, we present numerical examples to analyze the effect of different parameters on the pricing strategy decisions, including initial quality (q_0), deterioration rate (λ) and relative elasticity (γ). Parameter values extracted from previous work (Wang et al. 2012; Li and Wang 2017) are combined with the current grocery retailer practices as the inputs for the numerical analysis. $\Delta\pi\%$, defined as $\Delta\pi\% = \frac{\pi_{r2}(p_{21},p_{22},T_1)-\pi_{r1}(p_1)}{\pi_{r1}(p_1)}$, is introduced to express the percentage of profit increase of the two-stage pricing strategy for the retailer. $\Delta\pi\% > 0$ means the two-stage pricing strategy is better than the single pricing strategy for the retailer. In addition, we also examine the profit difference for the whole food supply chain. For unified parameter assignment, we set $D_0 = 9.79$ and $c = 3.99£/\mathrm{unit}$.

5.1 Effect of initial quality (q_0)

Initial quality affects pricing decisions by influencing the length of sales cycle and the total market demand. Set $\alpha = 1.83$, $\beta = 1.83, \lambda = 0.0067/h$. The effects of q_0 on the two-price markdown cost critical thresholds (M_1 and M_2) for the retailer and the whole supply chain are shown in Figure 2, which leads to three decision regions. Region I means that the two-stage price strategy leads to Pareto improvement, which increases the profit margin of both the retailer and the supplier. Region II describes the situation in which there is an increase in total profit for the whole supply chain but not the retailer. Region III refers to the situation where the single pricing strategy delivers better performance for the whole food supply chain.

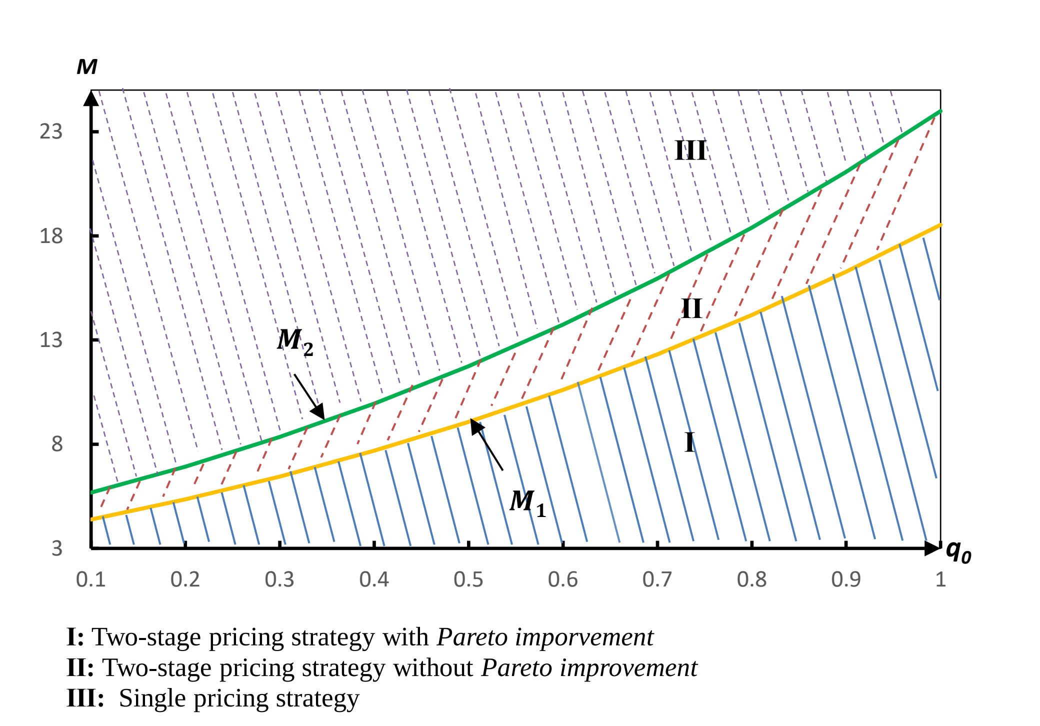


Figure 2 Effect of initial quality (q_0)

The result in Figure 2 shows that an increase of q_0 will increase the two critical thresholds (M_1 and M_2), whose relationship with the price markdown cost determines whether the two-stage pricing strategy should be adopted. It is evident that the value of perishable foods, which is reflected in the initial quality (q_0), has a positive impact on the benefit gained from the two-stage pricing strategy. As seen, the thresholds of price markdown cost for the two-stage pricing strategy are lower with a high initial quality value. In such a case, it is more likely for the retailer and the whole supply chain to benefit from the two-stage pricing strategy. Therefore, the initial quality level is an important factor that should be taken into consideration when choosing pricing strategies.

5.2 Effect of deterioration rate (λ)

The speed of food quality deterioration is often an important factor influencing grocery retailers' pricing decisions (Blackburn and Scudder 2009; Wang and Li 2012). Now, we set $q_0 = 0.95$, $\alpha = 1.83$, $\beta = 1.83$, and examine the effects of λ on the two critical thresholds M_1 and M_2. The result is shown in Figure 3 and again, the optimal pricing decisions are classified into three decision regions by the two critical thresholds. Interestingly, an increase in the quality deterioration rate reduces the value of the two critical thresholds (M_1 and M_2), which means that it is more likely for the retailer and the whole food supply chain to benefit from the single pricing strategy with a high deterioration rate λ. This finding is different from some industrial practices that discount price or regularly mark down the price of perishable foods with fast quality degradation such as meat and vegetable products. This can be explained by consumer delay in purchasing, waiting for a reduced price. In fact, it is more appropriate to implement the single pricing strategy for food products with short shelf-lives.

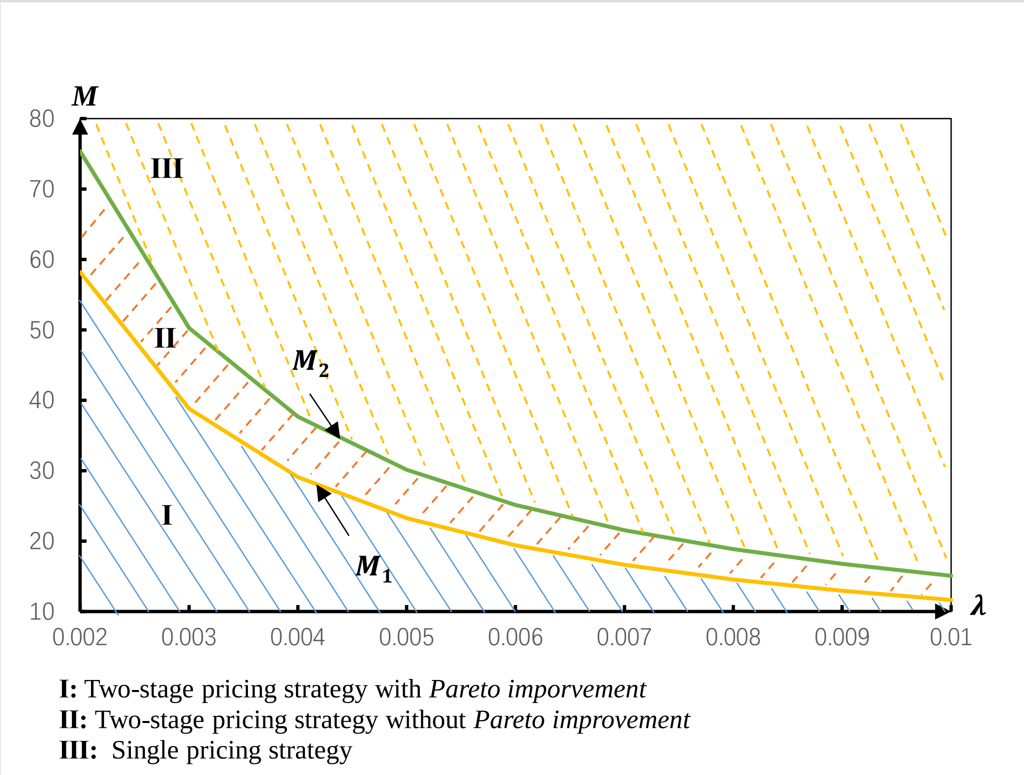
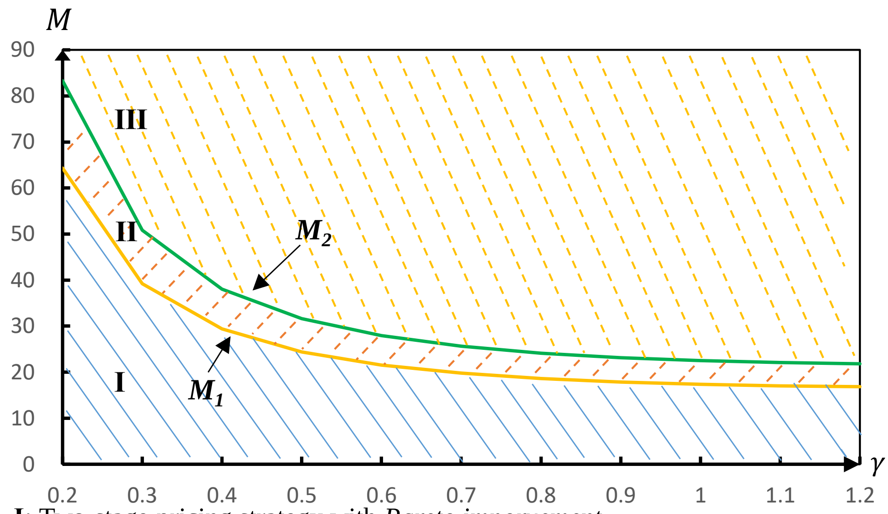


Figure 3 Effect of deterioration rate (λ)

5.3 Effect of relative elasticity (γ)

Relative elasticity reflects the relative impact of price and quality on demand of perishable goods. Here, we introduce the demand elasticity ratio γ, defined as $\gamma = \frac{\alpha}{\beta}$, to investigate how the relative elasticity affects pricing decisions. Here, $\gamma > 1$ means the influence of the price sensitivity factor (α) is stronger than the quality sensitivity factor (β). Let $\alpha = 1.83$, $q_0 = 0.95$, $\lambda = 0.0067/h$. We simulate different values of γ by changing β. Similar to the previous analysis, the effects of γ on the two critical thresholds (M_1 and M_2) are shown in Figure 4. When the elasticity ratio is low (a relatively low value of α or a relatively high value of β), both critical thresholds are high. Therefore, it does not require a low cost of price markdown to benefit from the two-stage pricing strategy. In this case, it is more likely for the retailer and the whole supply chain to benefit from the two-stage pricing strategy. In contrast, the two thresholds decease when the elasticity ratio (γ) increases. The degree of decrease in the two thresholds slows when the elasticity ratio reaches a certain level (e.g., $\gamma > 1$), indicating that it is more likely for the retailer and the whole food supply chain to benefit from the single pricing strategy if customer demand is more sensitive to price than quality. What is intuitive is clear: there is no need to mark down food price if consumer demand is not sensitive to food quality deterioration.



I: Two-stage pricing strategy with *Pareto imporvement*
II: Two-stage pricing strategy without *Pareto improvement*
III: Single pricing strategy

Figure 4 Effect of relative elasticity γ

5.4 Managerial implications

The insights generated through modeling and numerical analysis provide some important managerial implications to retailers and suppliers in the food supply chain. For instance, the result of our analysis demonstrates that it should not be compulsory to apply the two-stage pricing strategy (i.e., price markdowns) to perishable food products with short shelf lives (i.e., a high quality deterioration rate). In fact, whether grocery retailers should implement the two-stage pricing strategy depends on the price adjustment cost and its relationship to the critical thresholds identified in this research. Nevertheless, these two critical thresholds are also influenced by other model parameters such as initial quality level, quality deterioration rate and demand elasticity. Instead of marking down the prices of food products that are approaching their shelf lives, these important factors have to be considered before the implementation of any pricing strategies. Furthermore, for the product types for which the two-stage pricing strategy is more likely to deliver better financial performance for the food retailer and the food supply chain, food organizations should also explore ways to reduce price adjustment cost to pursue a more regular price discounting strategy for perishable foods. Finally, we also observed that in the situation in which the multistage pricing strategy benefits the whole supply chain but decreases the retailer's profit, food suppliers should take supply chain coordination mechanisms initiatives to encourage food retailers to adopt the multiple-stage pricing strategy.

6. Conclusions

This paper investigates the optimal pricing strategy for perishable foods from the perspective of a two-echelon supply chain composed of a suppler and a retailer. Using the game theory approach, we derive the equilibrium points for the single pricing strategy and the two-stage pricing strategy. Through a comparison of the equilibrium points, we analyzed how the two pricing strategies affect the supply chain's decisions as well as the supply chain members' individual and collective performances. Our analysis generates some novel insights. For instance:

- Whether the retailer benefits from the two-stage pricing strategy depends on the price markdown cost and its relationship with the critical threshold (M_1) that is determined by a combination of factors including the potential market size, the price and quality sensitivity factors, the initial quality, the unit product cost, and the quality deterioration rate. A similar rule applies to the whole supply chain although the critical threshold M_2 is higher than M_1. Interestingly, the supplier is always better off with the two-stage pricing strategy.

- Compared to the single pricing strategy, the advantage of the two-stage pricing strategy is mainly contributed by an induced customer demand as such a pricing strategy captures the quality deterioration of perishable food and sets a markdown price reflecting its quality degradation. It is the trade-off between the increased demand and incurred cost (i.e., price markdown cost) that determines whether the retailer and the whole supply chain will benefit from the two-stage pricing strategies. In principle, this trade-off is governed by the price markdown cost (M) and its relationship with the two critical thresholds (M_1 and M_2).
- This research provides some important managerial implications for food organizations. For instance, our analysis clearly specifies the conditions under which food retailers should adopt different pricing strategies. When the two-pricing strategy is the more favorable strategy, we do not only derive the optimal price but also the price markdown timing, which is useful for retailers to implement the pricing strategy. Finally, we also find that in the situation in which the retailer is worse off but the supply chain is better off, the perishable food supply chain can be coordinated through a profit-sharing contract to achieve a win-win outcome.

Like other studies using a modeling approach, this research has several limitations. First, for simplification, the quality deterioration rate was assumed to be linear with time. In fact, the quality deterioration rate of perishable food varies among different product categories (Rong et al. 2011; Wang and Li 2012). A future extension is to explore different forms (i.e., exponential) of quality degradation in the modeling. In addition, our model only discusses a supply chain setting consisting of one retailer and one supplier using linear deterministic demand. An important extension is to consider stochastic demand (Chen and Wang 2016; He et al. 2018) and investigate multiple retailers and suppliers. Finally, the pricing strategies for the perishable food supply chain were modeled in the setting of a balanced power relationship between the retailer and suppliers. A future extension is to explore how different power relationships affect the pricing decisions and performance of the perishable food supply chain (Shi et al. 2013; Chen and Wang 2015; Chen et al. 2017).

Acknowledgments

This research is partially supported by the National Natural Science Foundation of China (No. 71272128, 71432003, 91646109).

References

Adenso-Díaz, B., Lozano, S. and Palacio, A., 2017. Effects of dynamic pricing of perishable products on revenue and waste. *Applied Mathematical Modelling*, 45, 148-164.

Ahumada, O. and Villalobos, J.R., 2009. Application of planning models in the agri-food supply chain: A review. *European Journal of Operational Research*, 196(1), 1-20.

Aung, M.M. and Chang, Y.S., 2014. Temperature management for the quality assurance of a perishable food supply chain. *Food Control*, 40, 198-207.

Beske, P., Land, A. and Seuring, S., 2014. Sustainable supply chain management practices and dynamic capabilities in the food industry: A critical analysis of the literature. *International Journal of Production Economics*, 152, 131-143.

Blackburn, J., and Scudder, G. 2009. Supply chain strategies for perishable products: the case of hresh produce. *Production and Operations Management* 18 (2), 129-137.

Cai, X., Feng, Y., Li, Y. and Shi, D., 2013. Optimal pricing policy for a deteriorating product by dynamic tracking control. *International Journal of Production Research*, 51(8), 2491-2504.

Chen, X., Wang, X. 2015. Free or bundled: Channel selection decisions under different power structures. *OMEGA-International Journal of Management Science*, 53, 11-20.

Chen, X. and Wang, X. 2016. Effects of carbon emission reduction policies on transportation mode selections with stochastic demand. *Transportation Research Part E: Logistics and Transportation Review*, 90, 196-205.

Chen, X., Wang, X., Jiang, X., 2016. The impact of power structure on retail service supply chain with an O2O mixed channel. *Journal of the Operational Research Society*, 67(2), 294-301.

Chen, X., Wang, X., Chan, H., 2017. Manufacturer and retailer coordination for environmental and economic competitiveness: a power perspective. *Transportation Research Part E: Logistics and Transportation Review*, 97, 268-281.

Choi, S. C. 1996. Price competition in a duopoly common retailer channel. *Journal of Retailing*, 72 (2), 117-134.

Chung, J. and Li, D., 2014. A simulation of the impacts of dynamic price management for perishable foods on retailer performance in the presence of need-driven purchasing consumers. *Journal of the Operational Research Society*, 65(8), 1177-1188.

Dolgui, A., Tiwari, M.K., Sinjana, Y., Kumar, S.K. and Son, Y.J., 2018. Optimising integrated inventory policy for perishable items in a multi-stage supply chain. *International Journal of Production Research*, 56(1-2), 902-925.

Fan, L., Friesz, T., Yao, T., Chen, X., 2013. Strategic pricing and production planning using a Stackelberg differential game with unknown demand parameters. *IEEE Transactions on Engineering Management*, 60(3), 581-591.

Feedback (2018) How supermarkets drive food waste on UK farms, New report, https://feedbackglobal.org/2018/02/22-february-2018-new-report-supermarkets-drive-food-waste-uk-farms/, accessed 31/03/2018

Ferguson, M., Ketzenberg, M., 2006. Information sharing to improve retail product freshness of perishables. *Production and Operations Management*, 15(1), 57-73.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R. and Meybeck, A. 2011, Global Food Losses and Food Waste, Food and Agriculture Organisation of the United Nations (FAO), Rome.

He, Y., Huang, H., Li, D., Shi, C. and Wu, S.J., 2018. Quality and operations management in food supply chains: A Literature Review. *Journal of Food Quality*, 2018, 7279491, 1-14.

Herbon, A., Levner, E. and Cheng, T.C.E., 2014. Perishable inventory management with dynamic pricing using time–temperature indicators linked to automatic detecting devices. *International Journal of Production Economics*, 147, 605-613.

Huang, H., He, Y. and Li, D., 2018a. Pricing and inventory decisions in the food supply chain with production disruption and controllable deterioration. *Journal of Cleaner Production*, 180, 280-296.

Huang, H., He, Y. and Li, D., 2018b. Coordination of pricing, inventory, and production reliability decisions in deteriorating product supply chains. *International Journal of Production Research*, 56(18), 6201-6224.

La Scalia, G., Settanni, L., Micale, R. and Enea, M., 2016. Predictive shelf life model based on RF technology for improving the management of food supply chain: a case study. International

Journal of RF Technologies, 7(1), 31-42.

Li, D. and Wang, X. 2017, Dynamic supply chain decisions based on networked sensor data: an application in the chilled food retail chain. *International Journal of Production Research*, 55(17), 5127-5141.

Li, D., Wang, X., Chan, H. K. and Manzini, R. 2014 Sustainable food supply chain management, *International Journal of Production Economics*. 152, 1-8.

Liu, G., Zhang, J. and Tang, W., 2015. Joint dynamic pricing and investment strategy for perishable foods with price-quality dependent demand. *Annals of Operations Research*, 226(1), 397-416.

Lu, J., Zhang, J. and Qin, Y., Wang, J. and Wei, C., 2014. Joint pricing and inventory control for fresh produce and foods with quality and physical quantity deteriorating simultaneously. *International Journal of Production Economics*, 152, 42-48.

Lu, J., Zhang, J. and Zhang, Q., 2018. Dynamic pricing for perishable items with costly price adjustments. *Optimization Letters*, 12(2), 347-365.

Luo, Z., Chen, X., Chen, J., Wang, X. 2017. Optimal pricing policies for differentiated brands under different supply chain power structures. *European Journal of Operational Research*, 259(2), 437-451.

Modak, N.M., Panda, S. and Sana, S.S., 2016. Pricing policy and coordination for a distribution channel with manufacturer suggested retail price. *International Journal of Systems Science: Operations & Logistics*, 3(2), 92-101.

Navarro, K.S., Chedid, J.A., Caruso, N.M. and Sana, S.S., 2018. An inventory model of three-layer supply chain of wood and furniture industry in the Caribbean region of Colombia. *International Journal of Systems Science: Operations & Logistics*, *5*(1), 69-86.

Rong, A., Akkerman, R. and Grunow, M., 2011. An optimization approach for managing fresh food quality throughout the supply chain. *International Journal of Production Economics*, 131(1), 421-429.

Roy, A., Sana, S.S. and Chaudhuri, K., 2016. Joint decision on EOQ and pricing strategy of a dual channel of mixed retail and e-tail comprising of single manufacturer and retailer under stochastic demand. *Computers & Industrial Engineering*, 102, 423-434.

Roy, A., Sana, S.S. and Chaudhuri, K., 2018. Optimal pricing of competing retailers under uncertain demand-a two layer supply chain model. *Annals of Operations Research*, 260(1-2), 481-500.

Shi, R., Zhang, J., and Ru, J., 2013. Impacts of power structure on supply chains with uncertain demand. *Production and Operations Management*, 22(5), 1232-1249.

Soto-Silva, W.E., Nadal-Roig, E., González-Araya, M.C. and Pla-Aragones, L.M., 2016. Operational research models applied to the fresh fruit supply chain. *European Journal of Operational Research*, 251(2), 345-355.

The Food Rush, 2016. 5 things supermarkets can (and should) do about food waste, planet friendly. Article, https://www.thefoodrush.com/articles/5-things-supermarkets-can-food-waste/, accessed on 31/03/2018.

The Telegraph, 2016. Look inside the UK's first 'food waste' supermarket, News, https://www.telegraph.co.uk/news/2016/09/21/look-inside-the-uks-first-food-waste-supermarket/, accessed on 31/03/2018.

Tiwari, S., Sana, S.S. and Sarkar, S., 2018. Joint economic lot sizing model with stochastic demand and controllable lead-time by reducing ordering cost and setup cost. *RACSAM*, 112, 1075-1099.

Tsiros, M., Heilman, C. M., 2013. The effect of expiration dates and perceived risk on purchasing behavior in grocery store perishable categories. *Journal of Marketing*, 69(2), 114-129.

Wang, X., Fan, Z.P. and Liu, Z., 2016. Optimal markdown policy of perishable food under the consumer price fairness perception. *International Journal of Production Research*, 54(19), 5811-5828.

Wang, X., Li, D., O'brien, C. and Li, Y., 2010. A production planning model to reduce risk and improve operations management. *International Journal of Production Economics*, 124(2), 463-474.

Wang, X., Li, D., 2012. A dynamic product quality evaluation based pricing model for perishable food supply chains. *OMEGA-International Journal of Management Science,* 40(6), 906-917.

Willem, A., Roberto, R., Jack, G., 2014. Effective sourcing strategies for perishable product supply chains. *International Journal of Physical Distribution & Logistics Management*, 44(6), 494-510.

Wilhelm, M., Blome, C., Bhakoo, V., Paulraj, A. 2016. Sustainability in multi-tier supply chains: Understanding the double agency role of the first-tier supplier. *Journal of Operations Management*, 41, 42-60.

Yu, M. and Nagurney, A., 2013. Competitive food supply chain networks with application to fresh produce. *European Journal of Operational Research*, 224(2), 273-282.

Zhang, Q., 2018. Dynamic pricing for perishable items with costly price adjustments. *Optimization Letters*, 12(2), 347-365

Zhu, Z., Chu, F., Dolgui, A., Chu, C., Zhou, W. and Piramuthu, S., 2018. Recent advances and opportunities in sustainable food supply chain: a model-oriented review. International Journal of Production Research, 56(17), 5700-5722

Appendix

Proof of Lemma 1: Set $p_1 = m_1 + w_1$. From (1), we obtain $\pi_{r1}(p_1) = \pi_{r1}(m_1) = (m_1)[(D_0 - \alpha(m_1 + w_1) + \beta q_0)T - \frac{1}{2}\beta\lambda T^2]$, then $\frac{d\pi_{r1}(m_1)}{dm_1} = -\frac{1}{2}T(T\beta\lambda - 2D_0 + 4\alpha m_1 - 2\beta q_0 + 2\alpha w_1)$ and $\frac{d^2\pi_{r1}(m_1)}{d{m_1}^2} = -2\alpha T < 0$, so $\pi_{r1}(m_1)$ is a concave function of m_1. From (2), we obtain $\pi_{s1}(w_1) = (w_1 - c)\left[D_0 T - \alpha(m_1 + w_1)T + T\beta q_0 - \frac{1}{2}T^2\beta\lambda\right]$, then $\frac{d\pi_{s1}(w_1)}{dw_1} = D_0 T - \alpha(m_1 + w_1)T + T\beta q_0 - \frac{1}{2}T^2\beta\lambda - (w_1 - c)\alpha T$ and $\frac{d^2\pi_{s1}(w_1)}{d{w_1}^2} = -2\alpha T < 0$, so $\pi_{s1}(w_1)$ is a concave function of w_1. Let $\frac{d\pi_{r1}(m_1)}{dm_1} = \frac{d\pi_{s1}(w_1)}{dw_1} = 0$, we obtain $m_1 = -\frac{2c\alpha + T\beta\lambda - 2D_0 - 2\beta q_0}{6\alpha}$ and $w_1 = \frac{4c\alpha - T\beta\lambda + 2D_0 + 2\beta q_0}{6\alpha}$. Replace $T = \frac{D_0 - \alpha p_1 + \beta q_0}{\beta\lambda}$ to m_1 and w_1, then we obtain $m_1^* = \frac{-c\alpha + D_0 + \beta q_0}{4\alpha}$, $w_1^* = \frac{3c\alpha + D_0 + \beta q_0}{4\alpha}$ and $p_1^* = \frac{c\alpha + D_0 + \beta q_0}{2\alpha}$.

Proof of Lemma 2: From D_2 we obtain $T = \frac{D_0 - \alpha p_{22} + \beta q_0}{\beta\lambda}$. Set $p_{21} = m_{21} + w_2$ and $p_{22} = m_{22} + w_2$. From (4), we obtain $\pi_{r2}(p_{21}, p_{22}, T_1) = \pi_{r2}(m_{21}, m_{22}, T_1) = (m_{21} + w_2)\int_0^{T_1}[D_0 - \alpha(m_{21} + w_2) + \beta(-t\lambda + q_0)]\,dt + (m_{22} + w_2)\int_{T_1}^{T}[D_0 - \alpha(m_{22} + w_2) + \beta(-t\lambda + q_0)]\,dt) - w_2 D_2 - M$, then $\frac{\partial\pi_{r2}(m_{21}, m_{22}, T_1)}{\partial m_{21}} = -\frac{1}{2}T_1(-2D_0 + 4\alpha m_{21} - 2\beta q_0 + \beta\lambda T_1 + 2\alpha w_2)$, $\frac{\partial\pi_{r2}(m_{21}, m_{22}, T_1)}{\partial m_{22}} = -\frac{1}{2}(T - T_1)(T\beta\lambda - 2D_0 + 4\alpha m_{22} - 2\beta q_0 + \beta\lambda T_1 + 2\alpha w_2)$, $\frac{\partial\pi_{r2}(m_{21}, m_{22}, T_1)}{\partial T_1} = -(m_{21} - m_{22})(-D_0 + \alpha m_{21} + \alpha m_{22} - \beta q_0 + \beta\lambda T_1 + \alpha w_2)$ then from (5), we obtain $\pi_{s2}(w_2) = (w_2 - c)[\int_0^{T_1}\left(D_0 - \alpha(m_{21} + w_2) + \beta(q_0 - \lambda t)\right)dt + \int_{T_1}^{T}\left(D_0 - \alpha(m_{22} + w_2) + \beta(q_0 - \lambda t)\right)dt]$, then $\frac{d\pi_{s2}(w_2)}{dw_2} = Tc\alpha - \frac{1}{2}T^2\beta\lambda + TD_0 + T\beta q_0 - \alpha m_{21}T_1 + \alpha m_{22}(-T + T_1) - 2T\alpha w_2$ and $\frac{d{\pi_{s2}}^2(w_2)}{d{w_2}^2} = -2\alpha T < 0$, that is, $\pi_{s2}(w_2)$ is a concave function of w_2. From $\frac{\partial\pi_{r2}(m_{21}, m_{22}, T_1)}{\partial m_{21}} = \frac{\partial\pi_{r2}(m_{21}, m_{22}, T_1)}{\partial m_{22}} = \frac{\partial\pi_{r2}(m_{21}, m_{22}, T_1)}{\partial T_1} = \frac{d\pi_{s2}(w_2)}{dw_2} = 0$ and $T = \frac{D_0 - \alpha p_{22} + \beta q_0}{\beta\lambda}$, then we obtain $m_{21}^* = \frac{4(-c\alpha + D_0 + \beta q_0)}{13\alpha}$ $m_{22}^* = \frac{2(-c\alpha + D_0 + \beta q_0)}{13\alpha}$, $p_{21}^* = \frac{6c\alpha + 7D_0 + 7\beta q_0}{13\alpha}$, $p_{22}^* = \frac{8c\alpha + 5D_0 + 5\beta q_0}{13\alpha}$, $T_1^* = \frac{4(-c\alpha + D_0 + \beta q_0)}{13\beta\lambda}$, $w_2^* = \frac{10c\alpha + 3D_0 + 3\beta q_0}{13\alpha}$. Since $H_1 = \frac{\partial{\pi_{2r}}^2(m_{21}, m_{22}, T_1)}{\partial{m_{21}}^2}$, $H_1|_{m_{21}=m_{21}^*, m_{22}=m_{22}^*, T_1=T_1^*, w_2=w_2^*} = -\frac{8\alpha(-c\alpha + D_0 + \beta q_0)}{13\beta\lambda} < 0$, $H_2 =$

$\begin{vmatrix} \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial m_{21}{}^2} & \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial m_{21}\partial m_{22}} \\ \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial m_{22}\partial m_{21}} & \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial m_{22}{}^2} \end{vmatrix}$, $H_2|_{m_{21}=m_{21}^*,m_{22}=m_{22}^*,T_1=T_1^*,w_2=w_2^*} = \frac{64\alpha^2(-c\alpha+D_0+\beta q_0)^2}{169\beta^2\lambda^2} > 0$, $H_3 =$

$\begin{vmatrix} \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial m_{21}{}^2} & \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial m_{21}\partial m_{22}} & \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial m_{21}\partial T_1} \\ \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial m_{22}\partial m_{21}} & \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial m_{22}{}^2} & \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial m_{22}\partial T_1} \\ \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial T_1\partial m_{21}} & \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial T_1\partial m_{22}} & \frac{\partial \pi_{2r}{}^2(m_{21},m_{22},T_1)}{\partial T_1{}^2} \end{vmatrix}$, $H_3|_{m_{21}=m_{21}^*,m_{22}=m_{22}^*,T_1=T_1^*,w_2=w_2^*} =$

$-\frac{64\alpha(D_0-c\alpha+\beta q_0)^3}{2197\beta\lambda} < 0$. Then, m_{21}^*, m_{22}^*, T_1^* is the maximum point of $\pi_{r2}(m_{21}, m_{22}, T_1)$. So, $m_{21}^* = \frac{4(-c\alpha+D_0+\beta q_0)}{13\alpha}$ $m_{22}^* = \frac{2(-c\alpha+D_0+\beta q_0)}{13\alpha}$ $p_{21}^* = \frac{6c\alpha+7D_0+7\beta q_0}{13\alpha}$, $p_{22}^* = \frac{8c\alpha+5D_0+5\beta q_0}{13\alpha}$, $T_1 = \frac{4(D_0+\beta q_0-c\alpha)}{13\beta\lambda}$, $w_2^* = \frac{10c\alpha+3D_0+3\beta q_0}{13\alpha}$.

Proof of Proposition 1: From lemma 1 and lemma 2, we obtain $p_{21}^* - p_1^* = \frac{D_0+\beta q_0-c\alpha}{26\alpha} > 0$ and $p_1^* - p_{22}^* = \frac{3(D_0+\beta q_0-c\alpha)}{26\alpha} > 0$, then $p_{21}^* > p_1^* > p_{22}^*$. Similarly, from lemma 1 and lemma 2, we obtain $w_1^* - w_2^* = \frac{D_0+\beta q_0-c\alpha}{52\alpha} > 0$, that is, $w_1^* > w_2^*$.

Proof of Proposition 2: (1) From lemma 1 and equation (1), we obtain $\pi_{r1}(p_1^*) = \frac{(-c\alpha+D_0+\beta q_0)^3}{32\alpha\beta\lambda}$. Similarly, from lemma 2 and equation (4), we obtain $\pi_{r2}(p_{21}^*, p_{22}^*, T_1^*) = \frac{1}{2197\alpha\beta\lambda}(-80c^3\alpha^3 - 2197M\alpha\beta\lambda + 80D_0^3 + 240c^2\alpha^2\beta q_0 - 240c\alpha\beta^2 q_0^2 + 80\beta^3 q_0^3 - 240D_0^2(c\alpha - \beta q_0) + 240D_0(c\alpha - \beta q_0)^2)$. Then, $\pi_{r2}(p_{21}^*, p_{22}^*, T_1^*) - \pi_{r1}(p_1^*) = \frac{1}{70304\alpha\beta\lambda}[-363c^3\alpha^3 - 70304M\alpha\beta\lambda + 363D_0^3 + 1089c^2\alpha^2\beta q_0 - 1089c\alpha\beta^2 q_0^2 + 363\beta^3 q_0^3 - 1089D_0^2(c\alpha - \beta q_0) + 1089D_0(c\alpha - \beta q_0)^2]$. Let $\pi_{r2}(p_{21}^*, p_{22}^*, T_1^*) - \pi_{r1}(p_1^*) = 0$, we obtain $M_1 = \frac{363(D_0+\beta q_0-c\alpha)^3}{70304\alpha\beta\lambda}$. So, if $0 < M < M_1$, then $\pi_{r2}(p_{21}^*, p_{22}^*, T_1^*) > \pi_{r1}(p_1^*)$; if $M > M_1$, then $\pi_{r2}(p_{21}^*, p_{22}^*, T_1^*) < \pi_{r1}(p_1^*)$.

(2) From lemma 1 and equation (2), we obtain $\pi_{s1}(w_1^*) = \frac{(-c\alpha+D_0+\beta q_0)^3}{32\alpha\beta\lambda}$. Similarly, from lemma 2 and equation (5), we obtain $\pi_{s2}(w_2^*) = \frac{72(D_0+\beta q_0-c\alpha)^3}{2197\alpha\beta\lambda}$. Then, $\pi_{s2}(w_2^*) - \pi_{s1}(w_1^*) = \frac{107(D_0+\beta q_0-c\alpha)^3}{70304\alpha\beta\lambda} > 0$, that is, $\pi_{s2}(w_2^*) > \pi_{s1}(w_1^*)$.

(3) From lemma 1, equation (1) and equation (2), we obtain $\Pi_1^* = \pi_{r1}(p_1^*) + \pi_{s1}(w_1^*) =$

$\frac{(-c\alpha+D_0+\beta q_0)^3}{16\alpha\beta\lambda}$. Similarly, from lemma 2, equation (4) and equation (5), we obtain $\Pi_2^* = \pi_{r2}(p_{21}^*, p_{22}^*, T_1^*) + \pi_{s2}(w_2^*) = \frac{1}{2197\alpha\beta\lambda}(-152c^3\alpha^3 - 2197M\alpha\beta\lambda + 152D_0^3 + 456c^2\alpha^2\beta q_0 - 456c\alpha\beta^2 q_0^2 + 152\beta^3 q_0^3 - 456D_0^2(c\alpha - \beta q_0) + 456D_0(c\alpha - \beta q_0)^2)$. Then, $\Pi_2^* - \Pi_1^* = \frac{1}{35152\alpha\beta\lambda}(-235c^3\alpha^3 - 35152M\alpha\beta\lambda + 235D_0^3 + 705c^2\alpha^2\beta q_0 - 705c\alpha\beta^2 q_0^2 + 235\beta^3 q_0^3 - 705D_0^2(c\alpha - \beta q_0) + 705D_0(c\alpha - \beta q_0)^2)$. Let $\Pi_2^* - \Pi_1^* = 0$, we obtain $M_2 = \frac{235(D_0+\beta q_0-c\alpha)^3}{35152\alpha\beta\lambda}$. So, if $0 < M < M_2$, then $\Pi_2^* > \Pi_1^*$; if $M > M_2$, then $\Pi_2^* < \Pi_1^*$. $M_2 - M_1 = \frac{107(D_0+\beta q_0-c\alpha)^3}{70304\alpha\beta\lambda} > 0$, that is, $M_2 > M_1$.

Proof of Proposition 3: To achieve both the supplier and the retailer Pareto improvement, ρ should satisfy $\pi_{r2}(p_{21}^*, p_{22}^*, T_1^*) + \pi_{s2}(w_2^*) \times \rho > \pi_{r1}(p_1^*)$ and $\pi_{s2}(w_2^*) - \pi_{s2}(w_2^*) \times \rho > \pi_{s1}(w_1^*)$. Recalling lemma 1, lemma 2, equation (1), equation (2), equation (4) and equation (5), we obtain $\frac{2197M\alpha\beta\lambda}{72(D_0+\beta q_0-c\alpha)^3} - \frac{121}{768} < \rho < \frac{107}{2304}$. Set $\underline{\rho} = \frac{2197M\alpha\beta\lambda}{72(D_0+\beta q_0-c\alpha)^3} - \frac{121}{768}$ and $\bar{\rho} = \frac{107}{2304}$, we get $\rho \in (\underline{\rho}, \bar{\rho})$.